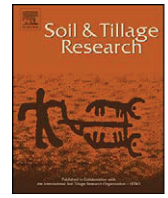
Soil & Tillage Research 106 (2010) 294–302

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still



Short-term effects of conservation agriculture on Vertisols under tef (*Eragrostis tef* (Zucc.) Trotter) in the northern Ethiopian highlands

Tigist Oicha [a,b,*], Wim M. Cornelis [c], Hubert Verplancke [c], Jan Nyssen [d], Bram Govaerts [e], Mintesinot Behailu [f], Mitiku Haile [b], Jozef Deckers [g]

[a] *Institute of Hydraulics and Rural Water Management, University of Natural Resources and Applied Life Sciences, Muthgasse, 18 A-1190 Vienna, Austria*
[b] *Department of Land Resource Management and Environmental Protection, Mekelle University, P.O. Box 231, Mekelle, Ethiopia*
[c] *Department of Soil Management, Ghent University, Coupure links, 653, B-9000 Gent, Belgium*
[d] *Department of Geography, International Centre for Eremology, Ghent University, Krijgslaan 281 (S8), B-9000 Gent, Belgium*
[e] *International Maize and Wheat Improvement Center (CIMMYT), Apdo. Postal 6-641, 06600 Mexico, D.F., Mexico*
[f] *Department of Natural Sciences, Coppin State University, Baltimore, MD 21216, USA*
[g] *Department of Earth and Environmental Sciences, Katholieke Universiteit Leuven, Celestijnenlaan 200E, B-3001 Heverlee, Belgium*

A R T I C L E   I N F O

Article history:
Received 4 July 2009
Received in revised form 7 November 2009
Accepted 9 December 2009

Keywords:
Conservation agriculture
Permanent bed
Aggregate stability
Runoff
Soil loss
Tef

A B S T R A C T

Soil erosion and declining soil quality are the major constraints for crop production and sustainable land management in Ethiopia. A conservation agriculture (CA) experiment was conducted in 2006 at Gumselasa, Northern Ethiopia, on experimental plots established in 2005 on a farmer's field. The objectives of this experiment were to evaluate the short-term changes in soil quality of a Vertisol due to the implementation of conservation agriculture practices and to assess their effect on soil erosion, crop yield and yield components of tef (*Eragrostis tef* (Zucc.) Trotter). The treatments were permanent bed (PB), *terwah* (TERW) and conventional tillage (TRAD). Soil organic matter (SOM) was significantly higher in PB (2.49%) compared to TRAD (2.33%) and TERW (2.36%). Although aggregate stability of PB (0.94) was higher than TRAD (0.83), the difference was not significant. PB had larger macroporosity (0.07 $m^3\ m^{-3}$) compared to the other treatments. PB reduced runoff volume by 50% and TERW by 16% compared to TRAD. PB also reduced soil loss by 86% and TERW by 53% in comparison to TRAD. Despite the above soil physical quality improvements and effectiveness in runoff and soil loss reduction, biomass and plant height of tef were significantly higher in TRAD than PB. The significantly high weed dry matter at first weeding, the types of weeds and their water uptake behavior might have caused the lower tef yield on the PB. We therefore recommend that appropriate rate of herbicides must be used while growing tef using CA practices.

1. Introduction

Agriculture in Ethiopia is dominated by low productive rainfed farming. The annual grain production, which averages 7 million tonnes, is too low to support national food demands (Eyasu, 2005). Land degradation in the form of soil erosion and declining soil quality is a serious challenge to agricultural productivity and economic growth (Mulugeta et al., 2005). Tigray, the northernmost region of the country, suffers from extreme land degradation as steep slopes have been cultivated for many centuries and are subject to serious soil erosion (Wolde et al., 2007). Rainfall is erratic and as a consequence there is strong seasonal (~8 months) moisture stress limiting the productivity of rainfed agriculture in the region (Haregeweyn et al., 2005). In addition to this problem, tillage in Ethiopia is carried out with a breaking ard plough, locally known as *maresha*, whose shape and structure have remained unchanged for thousands of years (Nyssen et al., 2000; Solomon et al., 2006).

The conventional tillage by *maresha* includes a primary tillage, followed by repeated secondary shallow tillage, aiming at controlling weeds, conserving moisture and aerating the soil (Melesse et al., 2008). In the study area, particularly since the widespread introduction of stone bunds for soil and water conservation in the late 1980s, plowing is done parallel to the contour. The first furrow is made at the lower end of the field, and the oxen move upslope for each subsequent furrow (Nyssen et al., 2000). These repeated operations cause moist soil to move to the surface favoring water loss by evaporation (Aase and Siddoway,

* Corresponding author at: Institute of Hydraulics and Rural Water Management, University of Natural Resources and Applied Life Sciences, Muthgasse, 18 A-1190 Vienna, Austria. Tel.: +43 1360065453; fax: +43 1360065499.
E-mail address: tigistder@yahoo.com (T. Oicha).

0167-1987/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2009.12.004

1982), exposing the soil to both wind and water erosion (Astatke et al., 2002; FAO, 2002) and causing structural damage (Melesse et al., 2008). Soil erosion due to high tillage frequency and other soil management problems has seriously affected over 25% of the Ethiopian highlands (Kruger et al., 1996). Such detrimental effect of soil erosion and water stress can be improved to some extent by other management options like conservation agriculture (CA) practices, including permanent beds and semi-permanent beds.

The main benefit of CA is to preserve the soil in semi-natural conditions as soil disturbance by cultivation is minimized and physicochemical degradation is reduced (Kertesz, 2004). Long-term application of CA practices has significantly reduced runoff in different soil types in different places (Lindstrom et al., 1997; Bosch et al., 2005; Zhang et al., 2007). Soil physical properties (infiltration rate, available water content, aggregate stability, and hydraulic conductivity) are also improved (Moreno et al., 1997; Crovetto, 1998; McGarry et al., 2000; Mikha and Rice, 2004; Whalen et al., 2004; Bosch et al., 2005; Limon-Ortega et al., 2006).

Recent policies in Tigray favor *in situ* water conservation, stubble management and the abandonment of free grazing (Nyssen et al., 2006). In line with this policy, conservation agriculture practices like permanent bed and semi-permanent bed have been introduced at experimental scale in Adigudom area (Fig. 1) starting from 2004/2005 with the aim to improve soil properties, conserve moisture, reduce runoff and soil loss on farmers' fields on Vertisols. Vertisols comprise about 12.6 million ha of land in Ethiopia, covering 10.3% of the total surface area of the country. Of this, only 25% of the soils are cultivated due to their poor physical quality (Bull, 1988; Jabbar et al., 2001). Vertisols have a great agricultural potential but poor workability; too hard when dry and too sticky when wet. They are among the most vulnerable soils to erosion depending on how they are managed and on their topsoil structure and texture (Deckers et al., 2001a; Moeyersons et al., 2006). Hence, selecting appropriate management options is of paramount importance while exploiting their potential for the growth of specific crop like tef (*Eragrostis tef* (Zucc.) Trotter.

Gebreegziabher et al. (2009) have conducted research on the Adigudom Vertisol using wheat as an indicator crop in their erosion assessment. However, it is important to study how the treatments respond for tef. Tef is endemic to Ethiopia and belongs to the family Poaceae (Gramineae) (Ingram and Doyle, 2003). It is the only cultivated cereal in the genus *Eragrostis* and consists of about 350 varieties (Abebe, 2001). Tef can be grown on a wide range of soil type; both under moisture stress and waterlogged conditions. It suffers less from diseases, gives better grain yield and possesses higher nutrient contents, especially protein, when grown on Vertisols rather than on Andosols (Seyfu, 1997). Tef is cultivated on about 2.1 M ha of land covering about 28% of the area under cereals in the country (CSA, 2005). Similar to grass, this crop offers a better soil cover and denser root system than other crops and hence has good value for erosion control, to the point that *Eragrostis* species are sometimes presented as a valid alternative for vetiver grass (Nyssen et al., 2009). Traditionally, this fine-grained cereal (l000-seed weighs only 265 mg, Seyfu, 1997) is cultivated with intensive seed bed preparations with 3–5 passes in semi-arid (Solomon et al., 2006; Melesse et al., 2008) and 5–8 passes in humid areas of the country (Fufa et al., 2001) using the ox-driven local *maresha*, aimed mainly to avoid weeds. The seed is then broadcasted over the surface of the seedbed after which it is mixed to the seedbed by use of thorny branches (Deckers et al., 2001b). Due to the dominance of the vertic soils in the area, tillage is very difficult and farmers associate this with injuries on the shoulders of the oxen. More labor input and longer time is needed to accomplish the plowing activity (Fassil, 2002).

In contradiction to the traditional belief, reduced tillage in experiments conducted in the central highland Vertisols with high rainfall have shown higher yield, although it was not statistically significant (Erkossa et al., 2006; Balesh et al., 2008). A similar study in the Adigudom Vertisol also showed promising results for the use of minimum tillage for tef growth (Habtegebrial et al., 2007). However, most of these studies stress only crop parameters and the gross margin of tef. There is little information on the effect of tillage practices on soil physical quality. Therefore, the objective of this study is to evaluate the impacts of CA practice, permanent beds together with *terwah* and traditional tillage, on changes in some soil physical quality indicators, soil erosion, tef yield and its yield components.

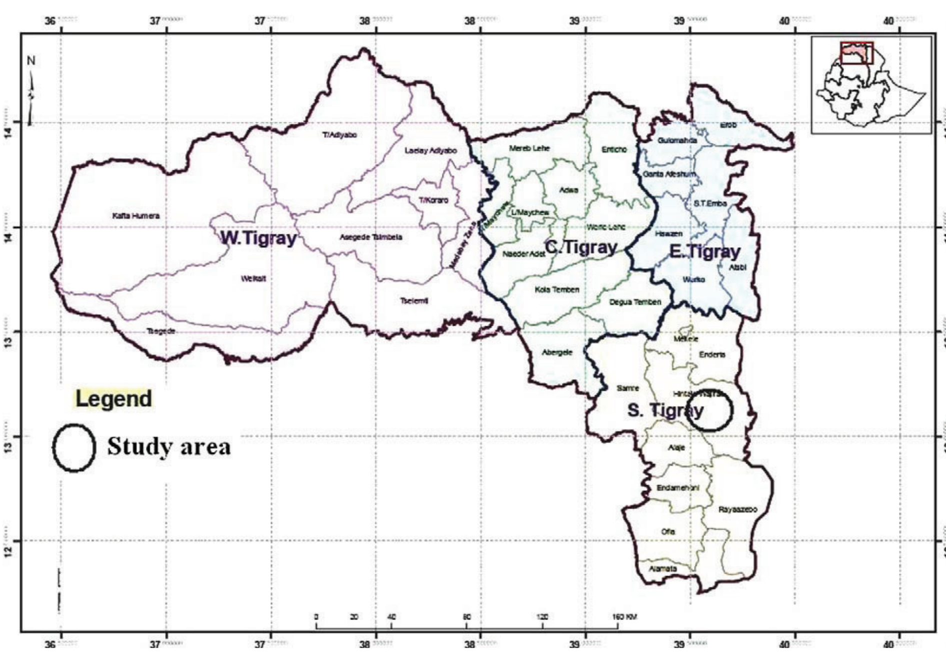


Fig. 1. Location map of the study area.

2. Materials and methods

2.1. The study site

The CA experiment began in January 2005 in Gumselasa (Adigudom), Northern Ethiopia (13°14′ N and 39°32′ E) located ~740 km north of Addis Ababa at an altitude of 1960 m a.s.l. (Fig. 1). The area has a cool tropical semi-arid climate, characterized by recurrent drought induced by moisture stress. Rainfall in the study site is unimodal, with >85% falling in the period of July–September (Fig. 2). The mean annual rainfall (26 yr) is 504.6 mm (MU-IUC, 2007) and the mean annual temperature is 23 °C. The average annual evapotranspiration was estimated as 1539 mm (NEDECO, 1997). According to USDA soil classification, the soil has a clay content of 73% and 24% silt content with high calcium content (20%) and high pH-$_{H_2O}$ (8.1). High pH is common in areas where annual precipitation is lower than annual evapotranspiration. Taking into account the swelling and shrinking characteristic which lead to wide and deep cracks during the dry season and the presence of neo-formed smectites (Nyssen et al., 2008), the soil is classified as pelli Calcic Vertisol according to WRB (1998) and Typic Calciustert according to Soil Survey Staff (USDA, 1999).

2.2. Experimental layout

The experiment was conducted on a farmer's field under rainfed conditions. All plowing and reshaping of furrows was done using the *maresha* (as described by Gebreegziabher et al., 2009). Tef was sown by broadcasting in all plots on August 4, 2006. The sowing rate was 30 kg ha^{-1} and the fertilizer rate was 100 kg ha^{-1} DAP and 50 kg ha^{-1} Urea for all treatments. The moisture content at sowing was 0.291 kg kg^{-1}. The experimental design was a randomized complete block with two replications for each of the following treatments:

1. Traditional tillage practice (TRAD): The land was plowed three times, once in May, once in July and the last time on the sowing date, just before broadcasting the seed.
2. *Terwah* (TERW): This is a traditional water conservation technique in which furrows are made by *maresha* along the contour at an interval of 1.5–2 m. It is similar to TRAD except for the furrows are made at regular intervals.
3. Permanent beds (PB): Beds and furrows of 60–70 cm width (middle of the furrow to the next one) were made after plowing the plots. The furrows were reshaped after every cropping season without any tillage on the top of the bed. In the current experiment, the furrows were reshaped in May and refreshed on the sowing date.

The whole experimental field was isolated from the upslope area by a 1.2 m wide and 0.5 m deep ditch to avoid any flow of water entering the upper side of the experimental field. The plots were separated from each other by a 0.5 m wide ditch, in order to avoid surface or subsurface hydrological 'contact' between them. The size of each plot was 19 m × 5 m and it had a 3% slope. Wheat was sown in the summer 2005 rainy season and tef in the rainy season of 2006. Runoff collection ditches at the bottom of each plot were lined with 0.5 mm thick plastic sheets to collect runoff and sediment generated from the experimental plots. The size of the trenches was ~1.5 m wide at the top, 4.5 m long and ~1 m deep. Trench depth and shape was variable and hence each trench was calibrated for volume–depth relationships.

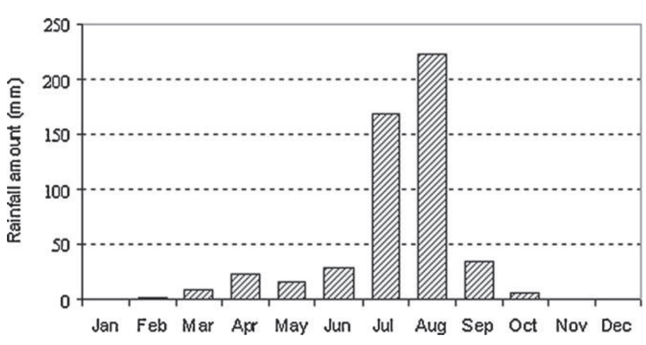


Fig. 2. Mean monthly rainfall in Adigudom (1972–2006).Source: MU-IUC (2007).

2.3. Soil sampling and analysis

Disturbed composite soil samples of 1.5 kg were collected from each plot from 0 to 20 cm depth in May 2006, prior to the first plowing for analysis of soil texture, soil organic matter (SOM), $CaCO_3$, soil shrinkage characteristic curve and aggregate stability. Undisturbed samples were also collected from each plot and soil depth to determine the soil water retention curve. Standard sharpened steel 100 cm^3 cylinders were driven into the soil using a dedicated ring holder (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands). The particle size distribution of the mineral components of the soils (i.e. after destruction of organic matter and $CaCO_3$) was determined using the combined sieve and pipette method (De Leenheer, 1959). SOM was determined using the Walkley and Black (1934) method, while $CaCO_3$ was determined by acid neutralization (De Leenheer, 1959).

The soil shrinkage characteristic curve (SSCC), describing the volume changes of clay soils with change in moisture content was determined using the balloon method as first described by Tariq and Durnford (1993) and slightly modified by Cornelis et al. (2006a). Soil samples (40–50 cm^3 of air-dried, crumbled soil) were passed through a 2 mm sieve, saturated with distilled water and put inside a rubber balloon taking care to avoid air entrapment. The samples were gradually dried by air flowing at low pressure over the sample and their volume and weight was recorded regularly by submergence in water. A simple four-parameter model as presented by Cornelis et al. (2006b) was then fitted through the observed void ratio e–moisture ratio ϑ data pairs:

$$e(\vartheta) = e_o + a\left[\exp\left(\frac{-b}{\vartheta^c}\right)\right] \quad (1)$$

where e_0 is the void ratio at oven-dryness (m^3 m^{-3}), and a, b and c are the fitting parameters determined by curve-fitting to observed SSCC data, for which we used Mathcad (2000) software. The moisture ratio ϑ (m^3 m^{-3}) was calculated as:

$$\vartheta = w\frac{\rho_s}{\rho_w} \quad (2)$$

where w is the gravimetric water content (kg kg^{-1}), ρ_s is the particle density (Mg m^{-3}) and ρ_w is the water density (Mg m^{-3}). The void ratio e (m^3 m^{-3}) can be written as:

$$e = \frac{\rho_s}{\rho_b} - 1 \quad (3)$$

where ρ_b is the bulk density (Mg m^{-3}).

The soil water characteristic curve (SWCC) was determined using the sandbox apparatus (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) for high soil matric potentials (0–0.01 MPa) and standard tension plate (Soilmoisture Equipment, Santa Barbara CA, USA) for low soil matric potentials (0.02–1.5 MPa), following the procedure outlined in Cornelis et al. (2005). Gravimetric water content was converted to volumetric water content using bulk density. The latter was computed for each data pair of the SWCC by combining the SSCC (Eq. (1)) with Eqs. (2) and (3). To fit the curve through the observed matric head h–volumetric water content θ data pairs, the Van Genuchten (1980) expression was used:

$$\theta = \theta_r + (\theta_s - \theta_r)\left[\frac{1}{1 + (\alpha|\psi|)^n}\right]^m \quad (4)$$

where θ_r and θ_s are the residual and saturated soil water content, respectively ($m^3\,m^{-3}$), ψ is the matric potential (cm), and α (in cm^{-1} for ψ in cm) and n (dimensionless) are the fitting parameters obtained by using RETC software (Van Genuchten et al., 1991). We restricted the number of fitting parameters to four, as suggested by Cornelis et al. (2005), with $m = 1 - 1/n$.

The SWCC was then used to compute the soil physical quality index (S) as defined by Dexter (2004), and macroporosity and matrix porosity, air capacity and plant-available water capacity according to Reynolds et al. (2007). Dexter (2004) defined S as the slope of the soil water retention curve at its inflection point and it can be written as:

$$S = -n(\theta_s - \theta_r)\left[\frac{2n-1}{n-1}\right]^{[1/n-2]} \quad (5)$$

The value of S is an indication of the extent to which soil porosity is concentrated into a narrow range of pore sizes and is assumed to be a measure of soil microstructure, which controls many soil physical properties. The residual water content θ_r was set at a zero value, as was also done by Dexter (2004). This parameter is mathematically defined as the water content where $d\theta/d\psi$ becomes zero or at $\psi = -\infty$ MPa, which is physically not realistic. Furthermore, θ_r often becomes negative in the curve-fitting procedure and as negative water content is undefined; it is then forced to converge to zero, which results as well in an unrealistic path of the retention curve at low water contents (Cornelis et al., 2005).

Macroporosity (MacPOR – ϕ_{mac}) and matric porosity (MatPOR – ϕ_{mat}) express the volume of macropores and matrix pores, respectively (Reynolds et al., 2007):

$$\phi_{mat} = \theta_m \quad (6)$$

$$\phi_{mac} = \theta_s - \phi_{mat} \quad (7)$$

where θ_m is the saturated volumetric water content exclusive of macropores (i.e. soil matrix porosity; $m^3\,m^{-3}$).

Reynolds et al. (2007) defined θ_m as the water content at a matric potential of −0.1 m (−1 kPa), or, when using the capillary rise equation (Jury and Horton, 2004), the water content contained in pores with diameters >300 μm. In contrast to Reynolds et al. (2007), we considered macropores as pores with a diameter >50 μm and thus related macroporosity to their functions in relation to plant growth, as suggested by Lal and Shukla (2004). Such pores correspond to transmission pores facilitating air movement and drainage of excess water (Greenland, 1977). According to this definition, θ_m is the water content at a matric potential of −0.6 m (−6 kPa).

The soil air capacity (AC), which is an indicator of soil aeration (Reynolds et al., 2007), was calculated as:

$$AC = \theta_s - \theta_{FC} \quad (8)$$

where θ_{FC} is the volumetric water content at so-called field capacity ($m^3\,m^{-3}$).

The latter (θ_{FC}) was determined gravimetrically on a 2 m × 2 m plot adjacent to our experimental site and with similar texture. An earth embankment was constructed along the four sides of the plot, which was ponded with water overnight to saturate the soil profile until 1 m depth. The plot was then covered with a plastic sheet to avoid evaporation and was left to drain under the influence of gravity. Soil samples taken from 0 to 20 cm after 48 h were used to determine the gravimetric water content at field capacity, and this value was converted to volumetric values using the SSCC.

Plant-available water capacity (PAWC), which expresses the soil's capacity to store and provide water that is totally available to plants, was calculated as:

$$PAWC = \theta_{FC} - \theta_{PWP} \quad (9)$$

where θ_{PWP} is the volumetric water content at permanent wilting point ($m^3\,m^{-3}$), which we assumed to correspond to a matric potential of −150 m (−1.5 MPa).

The stability of the soil aggregates to a depth of 20 cm was determined using the dry and wet sieving method of De Leenheer and De Boodt (1959). Soil samples were air-dried and 0.25 kg was sieved on sieves with mesh sizes of 8.00, 4.76, 2.83, 2.00, 1.00, 0.50 and 0.30 mm to obtain the aggregate-size distribution. Then, per fraction four subsamples were taken and pre-wetted until 'field capacity' by falling raindrops. After incubating the samples for 24 h, they were subjected to wet sieving. The stability of the aggregates to external forces was then expressed in terms of the stability index (SI):

$$SI = \frac{1}{MWD_{dry} - MWD_{wet}} \quad (10)$$

where MWD_{dry} and MWD_{wet} is the mean weighted diameter (mm) of the dry and wet sieving, respectively.

Runoff volume was measured at 8 a.m., each day after a storm that caused runoff, by measuring the depth of collected runoff in the trench using a graduated ruler and reducing the amount of direct rainfall into the ditches. The collected runoff was stirred thoroughly and ~4 l was collected from each trench using two 2 l plastic bottles for the determination of sediment concentration. Then the contents of runoff in each bottle were filtered separately in the laboratory using funnel and filter paper (Whatman #12), making the number of observations 12 for soil loss determination. Sediment on the filter paper was then oven-dried for 24 h at 105 °C and weighed.

Agronomic parameters (plant height at maturity, tef dry matter, yield, and weed dry matter) were collected. For the determination of yield, harvestable areas of 2 m × 8 m and 2 m × 6 m were delineated. Hand weeding was performed 4 and 8 weeks after sowing. The weed dry matter was determined by air-drying the first weeding. The Harvest Index was also calculated as the ratio of grain yield to the dry above-ground biomass.

2.4. Statistical analysis

ANOVA was used to test the statistical differences of soil physical properties and crop parameters between the management treatments. Mean comparison (student t-test, at alpha = 0.5) was conducted for parameters that were significantly different. The JMP version 5.0 (SAS Institute Inc., 2002) software was used for analysis.

3. Results

3.1. Soil organic matter and aggregate stability

PB had significantly higher ($p = 0.0003$) soil organic matter (SOM) than TRAD and TERW, while the latter two didn't show a significant difference (Fig. 3). Although the stability index of aggregates in PB was higher than for the TERW and TRAD (Fig. 4), the differences among the three treatments were not significant. There was no significant difference among the different size classes for the three treatments either (data not shown).

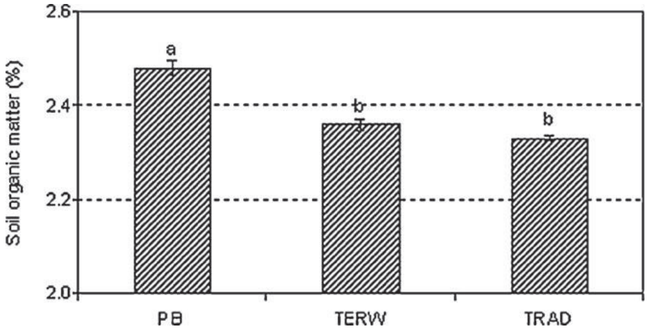


Fig. 3. Mean soil organic matter ($\pm$SE) for the three treatments for 0–20 cm soil depth (n = 6).

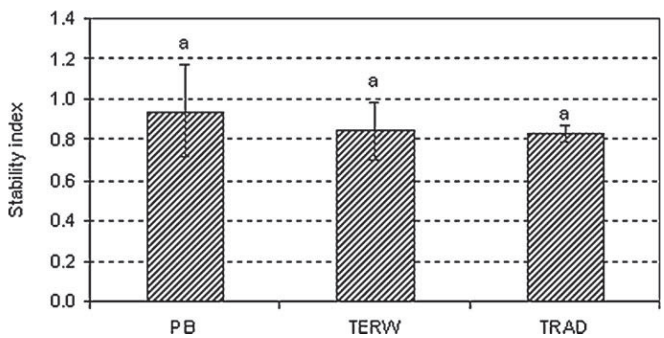


Fig. 4. Mean aggregate stability index ($\pm$SE) for the three treatments for 0–20 cm soil depth (n = 12).

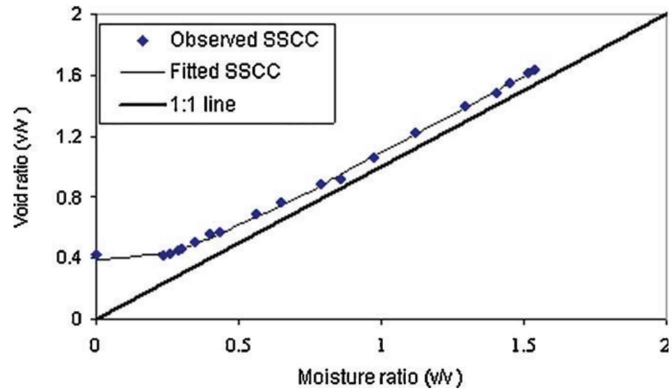


Fig. 5. Soil shrinkage characteristic curve fitted according to the model of Cornelis et al. (2006b) for samples collected from 0 to 20 cm.

3.2. Soil water characteristic curve and derived soil physical quality parameters

Table 1 shows soil moisture content at saturation (θ_s), S, MatPOR, MacPOR, θ_{PWP}, AC and PAWC values as calculated for the different treatments. PB and TRAD have relatively higher moisture content near saturation compared to TERW. The field-derived water content at field capacity was 0.510 $m^3 m^{-3}$ for the site. This corresponds to matric potential values between -100 and -200 kPa, when using the SWCC (figure not shown). The SSCC developed for the site is presented in Fig. 5. The bulk density and void ratio at oven dryness was 1.87 Mg m^{-3} and 0.39, respectively. PB had higher MacPOR (0.070 $m^3 m^{-3}$) compared to TRAD (0.063 $m^3 m^{-3}$), while TERW (0.055 $m^3 m^{-3}$) had the lowest value (Table 1). TRAD showed higher MatPOR followed by PB, whereas TERW had the lowest value. PB and TRAD had equivalent AC values, 0.087 $m^3 m^{-3}$ and 0.088 $m^3 m^{-3}$, respectively, which are higher than that of TERW (0.059 $m^3 m^{-3}$). The θ_{PWP} of all the treatments is similar ($\sim$0.35 $m^3 m^{-3}$). The PAWC of TERW (0.158 $m^3 m^{-3}$) and TRAD (0.159 $m^3 m^{-3}$) were slightly higher than PB (0.155 $m^3 m^{-3}$).

3.3. Runoff and soil loss

The runoff generated after each rainfall that caused runoff was not significantly different between the treatments in the first week after sowing (Fig. 6). Once the soil stabilized, however (i.e. after crop emergence) TRAD had significantly higher runoff volume than PB for a given rainfall amount. Nevertheless, the runoff generated from TERW and PB was not significantly different for the second and third week after sowing, although runoff from TERW was higher. After the furrows were filled with sediment TERW had the highest loss, although the loss was not significantly different from TRAD on days when rainfall was higher (i.e., August 27 and September 3 and 4, 2006). Even after the furrows were filled with sediment, TERW had significantly lower runoff compared to TRAD for most days with little rainfall. The overall runoff volume over the complete growing period showed that PB had significantly lower runoff than TRAD (Fig. 7). PB also showed lower runoff compared to TERW, though it was not significant. The mean of total runoff volume collected from TRAD, TERW and PB was 92.8, 78.2 and 46.7 mm, respectively.

Soil loss also followed a similar trend to runoff in the first week after sowing. However, there was a significantly higher soil loss from TRAD on August 9 when there was very high rainfall. Soil loss from TERW was significantly higher than for PB, unlike the runoff data during the third week after sowing. Soil loss was significantly higher in TRAD than the other two treatments by the end of the rainy season, especially when high rainfall occurred, unlike runoff where TRAD and TERW had no significant difference. There were significant differences among all treatments (Fig. 8) in overall soil loss (p = 0.0002).

3.4. Crop yield and its components

Results of grain yield analysis (Table 2) indicated a significant difference between PB (with a mean of 678 kg ha^{-1}) and TERW

Table 1
Soil moisture and bulk density at saturation calculated from SSCC, and soil physical quality index (S), matric porosity (ϕ_{mat}), macroporosity (ϕ_{mac}), water content at permanent wilting point (θ_{PWP}), plant available water content (PAWC) and air capacity (AC) calculated based on the Van Genuchten (1980) parameters of the soil water retention curve for the different treatments. Values with standard errors, α = 0.05, n = 6.

Treatments	Soil physical quality parameters							
	ρ_b (Mg m^{-3})	θ_s ($m^3 m^{-3}$)	S	ϕ_{mat} ($m^3 m^{-3}$)	ϕ_{mac} ($m^3 m^{-3}$)	θ_{PWP} ($m^3 m^{-3}$)	PAWC ($m^3 m^{-3}$)	AC ($m^3 m^{-3}$)
PB	0.98 ± 0.031a	0.596 ± 0.014a	0.067	0.527	0.070	0.355	0.155	0.087
TERW	1.05 ± 0.004a	0.569 ± 0.017a	0.06	0.514	0.055	0.352	0.158	0.059
TRAD	0.98 ± 0.021a	0.598 ± 0.009a	0.06	0.535	0.063	0.351	0.159	0.088

AC: Soil air capacity; CA: conservation agriculture; HI: harvest index; MacPOR = ϕ_{mac}: macroporosity; MatPOR = ϕ_{mac}: matric porosity; PAWC: plant available water content; PB: permanent bed; SOM: soil organic matter; S: soil physical quality index; SSCC: soil shrinkage characteristics curve; SWCC: soil water characteristics curve; SI: stability index; TERW: Terwah; TRAD: traditional tillage practice.

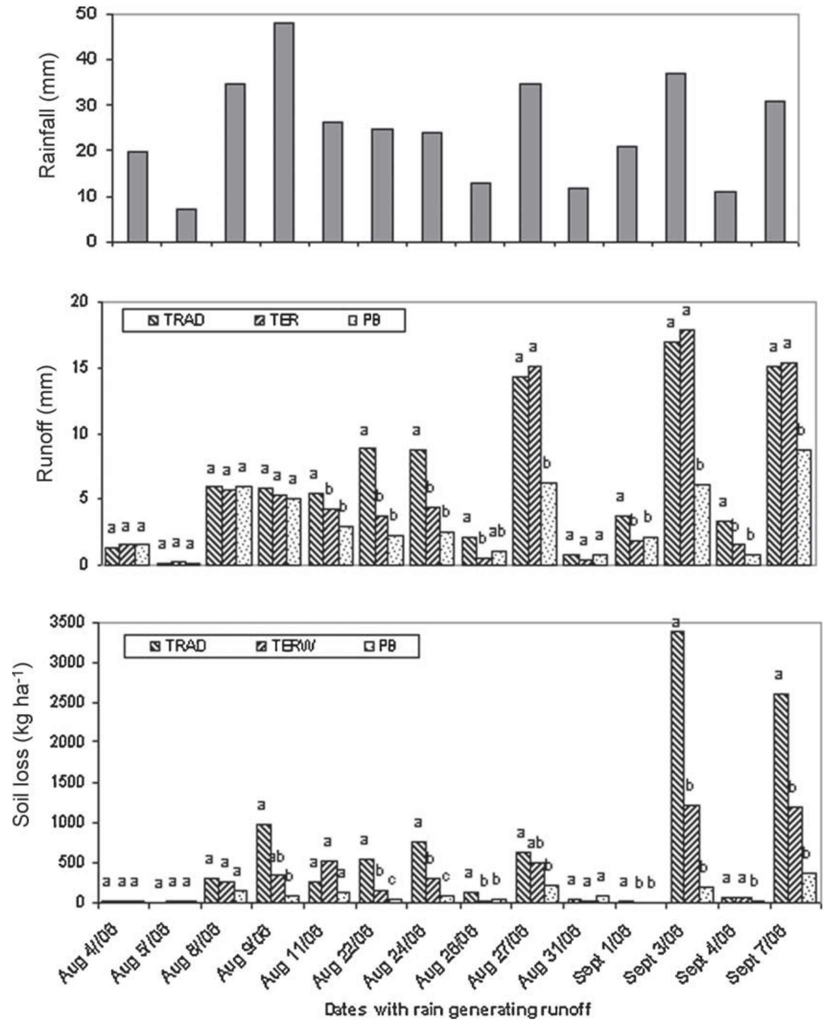


Fig. 6. Rainfall, runoff and sediment loss after each rainfall event that caused runoff for the different types of soil management practices: PB = permanent bed, TERW = Terwah, TRAD = traditional tillage practice. Same letters within each day indicate no significant difference.

(mean yield of 925 kg ha^{-1}). There was also a significant difference (p = 0.0016) among treatments in weed infestation. The mean mass of weed dry matter during the first weeding in the TRAD, TERW and PB was 77, 125 and 242 kg ha^{-1}, respectively. There was a significant ($p < 0.0001$) negative correlation (r = −0.956, n = 6) between weed dry matter and tef yield. Plant height at maturity was significantly higher for TRAD compared with both TERW and PB. The Harvest Index (HI) of PB and TERW was significantly (p = 0.01) higher than TRAD (Table 2). Although there was a significant difference in yield between treatments, no difference in tef biomass was observed between PB and TERW.

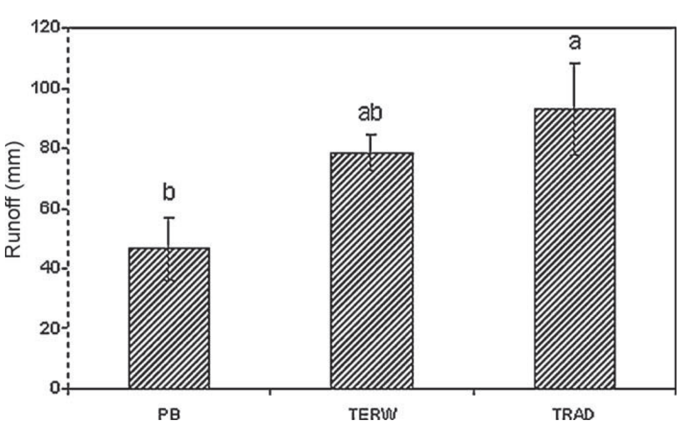


Fig. 7. Mean total runoff depth (±SE) for the growing period (n = 6).

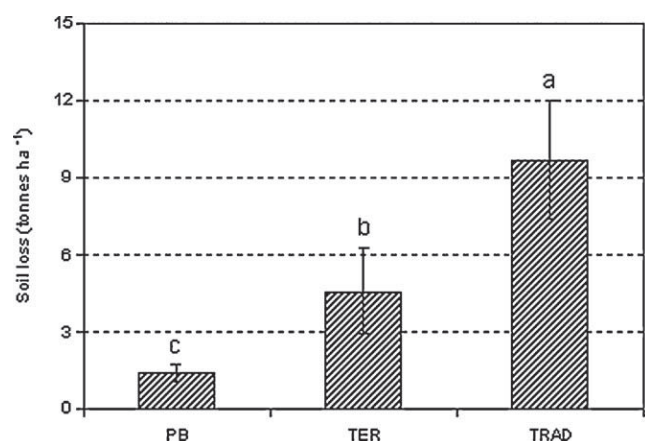


Fig. 8. Mean total soil loss (±SE) from each treatment during the whole growing period (n = 12).

Table 2
Agronomic parameters, mean tef yield, mean biomass, mean plant height, mean weed dry matter at first weeding and harvest index for the different treatments. Values between parenthesis are standard error ($\alpha = 0.05$, $n = 6$).

Treatment	Tef yield (kg ha^{-1})	Weed dry matter (kg ha^{-1})	Tef biomass (kg ha^{-1})	Plant height at maturity (cm)	Harvest index
TRAD	1173 (50)a	77 (4)c	6.7 (0.18)a	44 (2.5)a	0.18 (0.007)b
TERW	925 (99)b	125 (10)b	4.5 (0.64)b	39 (3.5)b	0.21(0.007)a
PB	678 (73)c	242 (17)a	3.0 (0.69)b	31(1.7)b	0.22 (0.004)a

Values with different letters within a column are statistically significant ($p < 0.05$).

4. Discussion

4.1. Soil organic matter and aggregate stability

The significantly higher SOM in PB was most probably from the incorporation of plant residue from the previous year. Christensen (1986) and Smith and Elliott (1990) reported that incorporation of straw and other organic materials promotes soil particle aggregation. Plant residues from the previous cropping season and less soil disturbance resulted in higher aggregate stability on PB and our result accords with findings by Gebreegziabher (2006) on the same experimental site in the previous year (2005). Higher aggregate stability was reported even in short-term application of reduced tillage or no till (D'Haene et al., 2008; Coppens et al., 2006). In cumulic Phaeozems in Mexico, Govaerts et al. (2007), found significantly higher aggregate stability on PB with full residue retention compared to those with residue removal. However, significant differences between the treatments may be obtained in the long term (Oorts et al., 2007), as the formation of aggregates is a gradual process. The higher stability index (SI) can contribute to improved infiltration of water and hence more soil water storage in PB than in the other treatments. According to the De Leenheer and De Boodt (1959) classification for stability index, our soils can be classified as 'good'. Generally the presence of cementing agents like $CaCO_3$, high clay content and the addition of residue resulted in good aggregate stability.

4.2. Soil physical properties and soil physical quality indicators

The high clay content caused more pronounced shrinkage in a way to have a very high bulk density and low void ratio at oven dryness. These values are similar to Cuban Vertisols (Cornelis et al., 2006a). According to Dexter (2004), the soil physical quality index of our soil was good because all S values were >0.035, which is the critical value. He stated that soils with high S than 0.035 have better soil microstructure than those with S value <0.035. However, it is questionable if the critical value suggested by Dexter (2004) is also applicable to shrinking soils. The high moisture content at saturation for PB can be due to large amounts of macropores produced by the cessation of tillage; whereas the reason for the high value in TRAD is presently unclear. The high MacPOR of PB relative to the other treatments might be due to less soil disturbance and addition of residue from the previous crop that had led to the formation of macropores. In Canada, two years application of no-till (NT) increased MacPOR rapidly on clay loam soil (Reynolds et al., 2007). Our finding is supported by the relatively high SOM in PB compared with TERW and TRAD, although it was not significant. The lower bulk density of PB at saturation compared to TERW also tells us that PB has larger MacPOR. Overall, the MacPOR of all treatments is in the range for undegraded soils, for medium to fine textured soils according to Drewry and Paton (2005). The soil MacPOR refers to pores with diameter >0.05 mm, whereas MatPOR refers to pores having equivalent diameters <0.05 mm. The higher MatPOR in TRAD is expected due to its lower MacPOR than that of PB. The MacPOR and MatPOR of TERW were lower than the other two treatments. The lower AC value of TERW relative to PB and TRAD could be due to the low moisture content at saturation. According to the suggestion of Cockroft and Olsson (1997), our soil has lower AC to compensate for low gas diffusion rates and the respirative demands of biological activity, although AC requirement of tef is not yet studied. This may be due to the inherent nature of Vertisols. There is no distinct difference in PAWC between treatments because permanent wilting point (PWP) values are quite similar as it is mainly affected by texture rather than soil structure. Moreover, Reynolds et al. (2007) mentioned that PAWC does not respond substantially in fine textured soils.

4.3. Runoff and soil loss

In the central highland Vertisols of Ethiopia, erosion experiments were conducted to test the effect of the Broad Bed Furrow (BBF) to drain excess water from the field (Erkossa et al., 2005). However, in the Vertisols of the northern highlands, water shortage is a serious problem and water conservation is a major concern. Accordingly, our experimental site was designed to study possible methods that can harvest as much moisture for healthy growth of different crops grown in the area to enhance *in situ* water conservation. Gebreegziabher et al. (2009) found over 60% decrease in total runoff using wheat as a test crop in the previous growing period, while we found 50% decrease in PB compared to TRAD. Our result accords with their findings. The runoff generated from all the treatments in the first week after sowing was not significantly different between treatments. This can be due to the disturbance of the field during reshaping and plowing at sowing. Once the soil was stabilized (i.e. after crop emergence), TRAD had a significantly higher runoff volume than PB for a given rainfall amount. Engel et al. (2009) found variation in runoff during the different growth stages of crops grown on their research under simulated rainfall. However, they also found significantly lower runoff from the NT treatment over the total growing period, as has been the case in our site. Soil management can have different impacts on runoff under different crops (Gebreegziabher et al., 2009). NT under young olive groves grown on heavy clay soil in Spain resulted in highest runoff and least soil physical quality compared to conventional tillage (Gomez et al., 2009). PB has reduced sediment loss by 85% and TERW by 70%. Long-term experiments under CA using simulated rain have shown significantly lower runoff in direct till and no till experiments compared with conventional tillage practices (Zhang et al., 2007; Jin et al., 2008; Jin et al., 2009). The higher soil loss measured on September 4 and 7, 2006 (Fig. 6) may be due to high intensity rainfall that caused more soil detachment, although crop cover was higher compared to the first weeks after sowing. Antecedent moisture and amount, duration and intensity of rainfall affect runoff amount. Runoff substantially increases as rain falls frequently and soil is saturated. The infiltration rate is reduced as deeper soil layers become saturated, since the hydraulic gradient decreases. This may have caused higher amounts of runoff at the end of the rainy season. Both for soil loss and sediment yield, our findings are consistent with those of Gebreegziabher et al. (2009). We therefore support their suggestion that TERW can be a better step towards permanent *in situ* moisture conservation and runoff reduction for all crops.

4.4. Agronomic parameters

The study shows that PB and TERW reduced tef yield and biomass production on the experimental site. In contrast to tef, Gebreegziabher (2006) found 30 and 33.3% higher yields of wheat (*Triticum* spp.) on TERW and PB, respectively, compared to TRAD, though the differences were not significant. This shows that the type of crop grown has different responses for the implemented soil water management systems on Vertisols (Erkossa et al., 2006). Habtegebrial et al. (2007) found higher moisture content in minimum tillage compared to conventional tillage near our experimental site. However, Seyfu (1997) reported that tef can grow both under moisture stress and waterlogged conditions. A greenhouse experiments by Ameha (2002) showed that the crop can grow at a matric potential of even as low as -3.7 MPa. This shows that the crop can resist water stress without reducing yield. The amount of rainfall in 2006 was ~110 mm more than the long-term average, so that even in TRAD, there was no shortage of water during the cropping season. Moreover, the PAWC of the three treatments were similar, evidencing that moisture stress may not be the reason for lower yield in PB and TERW. Waterlogging was also not observed during the growing period in our experiment. Tef is a weed sensitive crop and needs more frequent plowing, especially in heavy clay soils (Rockström et al., 2009; Seyfu, 1997; Taddesse, 1969). PB had significantly higher weed infestation than TRAD. Similar results were reported on zero tillage (Balesh et al., 2008) and minimum tillage on Vertisols in Ethiopia (Habtegebrial et al., 2007). Rezene and Zerihun (2001) reported yield loss of 23–65% due to weed competition. Therefore, the significantly lower production ($p = 0.0174$) of tef on PB compared to TERW and TRAD in this experiment could most probably be due to resource competition from high weed infestation. Balesh et al. (2008) reported lower grain yield and biomass on zero tillage compared to the other treatments in the central highland Vertisols of Ethiopia during the second year of their research. Researchers, however, suggest minimum or reduced tillage with herbicide application (Erkossa et al., 2006; Sasakawa Global, 2004) as a better option for tef production on Vertisols, because it yields slightly higher or almost similar grain yield compared to conventional tillage. The grain yield from TERW in our experiment is in the higher range of national average yield of tef, although it was lower than that of TRAD. Therefore, considering it as the first step towards PB may be a better option, as proposed by Gebreegziabher et al. (2009). The significantly higher HI on PB and TERW compared to TRAD ($p = 0.0100$) is in line with the strong negative correlation ($p < 0.005$, $n = 6$) of HI with yield and biomass of tef ($r = -0.97$ and $r = -0.99$, respectively).

5. Conclusions

This short-term research showed significantly higher SOM in PB compared to the other treatments. However, the SWCC shows that PB and TRAD had relatively higher moisture content near saturation compared to TERW. The relatively higher MacPOR of PB showed that the increase in the SOM and aggregate stability have contributed to this improvement. The effectiveness of TRAD and PB in runoff and soil loss reduction suggests that these soil management systems could be a requirement for all crops for better soil and water conservation. Despite the above improved soil physical properties and soil erosion reduction, which most probably resulted in higher soil water storage in PB than in the other treatments, yield, biomass and plant height of tef were significantly higher in TRAD than in PB. The significantly high weed dry matter at first weeding in PB, the types of weeds and their water uptake behavior have most probably caused the reduced tef yield.

Acknowledgements

This research was funded by the Institutional University Co-operation (IUC) Project in Mekelle University, through the Flemish Interuniversity Council (VLIR, Belgium). We are sincerely grateful to Melaku Weldekidan for his unreserved assistance during the fieldwork. We are grateful to Meresa Kiros, from the Bureau of Agriculture and Natural Resources who helped us during farmer's field selection of the experiment and during the whole cropping season. We would like to thank the owner of the field for his hospitality and the Soil Physics Laboratory staff of Ghent University and Mekelle University. Acknowledgements are extended to the constructive comments of two anonymous reviewers on an earlier version of this paper.

References

Aase, K., Siddoway, F., 1982. Evaporative flux from wheat and fallow in a semi-arid climate. Soil Sci. Am. J. 46, 619–626.
Abebe, D., 2001. Tef genetic resources in Ethiopia. In: Hailu, T., Getachew, B., Mark, S. (Eds.), Narrowing the Rift. Tef Research and Development: Proceedings of the International Workshop on Tef Genetics and Improvement, DebreZeit, Ethiopia, 16–19 October 2000, pp. 3–7.
Ameha, S., 2002. Influence of water availability on the growth of *Eragrotis tef*. M.Sc. Thesis. University of Ghent, Belgium.
Astatke, A., Jabbar, M., Tanner, D., 2002. Participatory conservation tillage research: an experience with minimum tillage on an Ethiopian highland Vertisol. Agric. Ecosys. Environ. 95, 401–415.
Balesh, T., Aune, J.B., Johansen, F.H., Vanlauwe, B., 2008. The prospects of reduced tillage in tef (*Eragrostis tef* Zucca.) in Gare Arera, West Shawa Zone of Oromiya, Ethiopia. Soil Tillage Res. 99, 58–65.
Bosch, B., Potter, T., Truman, C., Bednarz, C., Strickland, T., 2005. Surface runoff and lateral subsurface flow as a response to conservation tillage and soil water conditions. Trans. ASAE 48, 2137–2144.
Bull, A., 1988. Agro-ecological assessment of Ethiopia Vertisols. In: Jutzi, S.C., Haque, I., McIntire, J., Stares, J.E.S. (Eds.), Management of Vertisols in sub-Saharan Africa, Addis Ababa, Ethiopia. pp. 89–105.
Christensen, B.T., 1986. Barley straw decomposition under field conditions: effect of placement and initial nitrogen content on weight loss and nitrogen dynamics. Soil Biol. Biochem. 18, 523–529.
Cockroft, B., Olsson, K.A., 1997. Case study of soil quality in southeastern Australia: management of structure for roots in duplex soils. In: Gregorich, E.G., Carter, M.R. (Eds.), Soil Quality for Crop Production and Ecosystem Health. Developments in Soil Science. Elsevier, New York, NY, pp. 339–350.
Coppens, F., Merckx, R., Recous, S., 2006. Impact of crop residue location on carbon and nitrogen distribution in soil and water-stable aggregates. Eur. J. Soil Sci. 57, 570–582.
Cornelis, W., Khlosi, M., Hartmann, R., Van Meirvenne, M., De Vos, B., 2005. Comparison of unimodal analytical expressions for the soil-water retention curve. Soil Sci. Am. J. 69, 1902–1911.
Cornelis, W., Corluy, J., Medina, H., Hartmann, R., Van Meirvenne, M., Ruiz, M., 2006a. A simplified parametric model to describe the magnitude and geometry of soil shrinkage. Eur. J. Soil Sci. 57, 258–268.
Cornelis, W., Corluy, J., Medina, H., Diaz, J., Hartmann, R., Van Meirvenne, M., Ruiz, M., 2006b. Measuring and modelling the soil shrinkage characteristic curve. Geoderma 137, 179–191.
Crovetto, C., 1998. No-till development in Chequen Farm and its influence on some physical, chemical and biological parameters. Soil Water Conserv. 53, 194–199.
CSA, Central Statistics Authority, 2005. Agricultural Sample Survey 2004/2005. Report on Area and Production for Major Crops, vol. 1. Addis Ababa, Ethiopia.
D'Haene, K., Vermang, J., Cornelis, W., Leroy, B., Schiettecatte, W., De Neve, D., Gabriels, D., Hofman, G., 2008. Reduced tillage effects on physical properties of silt loam soils growing root crops. Soil Tillage Res. 99, 279–290.
De Leenheer, L., 1959. Werkwijzen van de analysen aan het Centrum voor Grondonderzoek. Rijkslandbouwhogeschool Gent, Ghent.
De Leenheer, L., De Boodt, M., 1959. Determination of aggregate stability by the change in mean weight diameter. Mededelingen van landbouwhogeschool en de opzoekingstations van de staat te Gent 24, 290–300.
Deckers, J., Spaargaren, O., Nachtergaele, F., 2001a. Vertisol: genesis, properties and soilscape management. In: Syers, K., Penning de Vries, F., Nymundeza, P. (Eds.), The Sustainable Management of Vertisols. CABI Publishing, New York, pp. 3–20.
Deckers, J., Teshome, Y., Negeri, A., Seyfu, K., 2001b. Teff. In: Raemaekers, R. (Ed.), Crop Production in Tropical Africa. Directorate General for International Cooperation, Brussels, pp. 96–101.
Dexter, R., 2004. Soil physical quality. Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma 120, 201–214.
Drewry, J., Paton, R., 2005. Soil physical quality under cattle grazing of a winter-fed brassica crop. Aust. J. Soil Res. 43, 525–531.

Engel, F.L., Bertol, S.R., Ritter, A., Paz Gonzalez, J., Paz-Ferreiro, E., Vidal, V., 2009. Soil erosion under simulated rainfall in relation to phenological stages of soybeans and tillage methods in Lages, SC, Brazil. Soil Tillage Res. 103, 216–221.

Erkossa, T., Stahr, K., Gaiser, T., 2005. Effect of different methods of land preparation on runoff, soil and nutrient losses from a Vertisol in the Ethiopian highlands. Soil Use Manage. 21, 253–259.

Erkossa, T., Stahr, K., Gaiser, T., 2006. Soil tillage and crop productivity on a Vertisol in Ethiopian highlands. Soil Tillage Res. 85, 200–211.

Eyasu, Y., 2005. Development and management of irrigated lands in Tigray, Ethiopia. Ph.D. Thesis. Department of Water Engineering, UNESCO-IHE Institute for Water Education, Delft, The Netherlands.

FAO, 2002. Crops and drops. Making the best use of water for agriculture. Rome, Italy. http://www.fao.org/DOCREP/005/Y3918E/Y3918E00.HTM (Accessed on July 7, 2007).

Fassil, K., 2002. Analysis of yield gaps and constraints for rainfed wheat production on Vertisols in the Tigray highlands, Ethiopia: case study in Adigudom. Ph.D. Thesis. Faculty of Sciences, Ghent University, Belgium.

Fufa, H., Tesfa, B., Hailu, T., Kibebew, A., Tiruneh, K., Aberra, D., Seyfu, K., 2001. Agronomy research in Tef. In: Hailu, T., Getachew, B., Mark, S. (Eds.), Narrowing the Rift. Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, Debre Zeit, Ethiopia, 16–19 October 2000, pp. 167–176.

Gebreegziabher, T., 2006. Effect of conservation agriculture with permanent bed and semi-permanent beds on soil water dynamics and soil loss in Gum-selasa, Southern Tigray, Ethiopia. M.Sc. Thesis. Faculty of Dryland Agriculture and Natural Resources, Mekelle University, Ethiopia.

Gebreegziabher, T., Nyssen, J., Govaerts, B., Fekadu, G., Mintesinot, B., Mitiku, H., Deckers, J., 2009. Contour furrows for *in situ* soil and water conservation, Tigray, Northern Ethiopia. Soil Tillage Res. 103, 257–264.

Gomez, J.A., Teodorico, A.S., Giraldez, V., Fereres, E., 2009. Soil management effects on runoff, erosion and soil properties in an olive grove of Southern Spain. Soil Tillage Res. 102, 5–13.

Govaerts, B., Sayre, K., Lichter, K., Dendooven, L., Deckers, J., 2007. Influence of permanent raised bed planting and residue management on physical and chemical soil quality in rain fed maize/wheat systems. J. Soil Plant 291, 39–54.

Greenland, D.J., 1977. Soil damage by intensive arable cultivation: temporary or permanent? Philos. Trans. R. Soc. Lond. Ser. B 281, 193–208.

Habtegebrial, K., Singh, B.R., Haile, M., 2007. Impact of tillage and nitrogen fertilization on yield, nitrogen efficiency of tef (*Eragrostis tef* (Zucc.) Trotter) and soil properties. Soil Tillage Res. 94, 55–63.

Haregeweyn, N., Poesen, J., Verstraeten, G., De Vente, J., Govers, G., Deckers, S., Moeyersons, J., 2005. Specific sediment yield in Tigray-Northern Ethiopia: assessment and semi-quantitative modelling. Geomorphology 69, 315–331.

Ingram, A.L., Doyle, J.J., 2003. The origin and evolution of *Eragrostis tef* (Poaceae) and related polyploids: evidence from nuclear *waxy* and plastid *rps*^{16}. Am. J. Bot. 90, 116–122.

Jabbar, M.A., Saleem, M.A.M., Li-Pun, H., 2001. Towards transdisciplinarity in technology and resource management research: a project in Ethiopia. Outlook Agr. 30, 257–260.

Jin, K., Cornelis, W., Gabriels, D., Schiettecatte, W., De Neve, S., Lu, J.J., Buysse, T., Wu, H.J., Cai, D.X., Jin, J.Y., Hartmann, R., 2008. Soil management effects on runoff and soil loss from field rainfall simulation. Catena 765, 191–199.

Jin, K., Cornelis, W.M., Schiettecatte, W., Lu, J.J., Cai, D.X., Jin, J.Y., De Neve, S., Hartmann, R., Gabriels, D., 2009. Effects of different soil management practices on total P and Olsen-P sediment loss: a field rainfall simulation study. Catena 78, 72–80.

Jury, W.A., Horton, R., 2004. Soil Physics, 6th ed. John Wiley & Sons, Hoboken, NJ.

Kertesz, A., 2004. Conventional and conservation tillage from pedological and ecological aspects. The SOWAP Project. In: Proceedings of the 4th International Congress of the European Society for Soil Conservation ''Soil Conservation in a Changing Europe'', Budapest, Hungary, 25–29 May 2004, pp. 33–135.

Kruger, H., Berhanu, F., Yohannes, G., Kefeni, K., 1996. Creating an inventory of indigenous soil and water conservation measures in Ethiopia. In: Reij, C., S-coones, I., Toulmin, C. (Eds.), Sustaining the Soil Indigenous Soil and Water Conservation in Africa. International Institute for Environment and Development, Earthscan, London.

Lal, R., Shukla, M., 2004. Principles of Soil Physics. Marcel Dekker, Inc., New York, p. 716.

Limon-Ortega, A., Govaerts, B., Deckers, J., Sayre, K., 2006. Soil aggregate and microbial biomass in a permanent bed wheat–maize planting system after 12 years. Field Crop Res. 97, 302–309.

Lindstrom, M., Schumacher, E., Cogo, P., Blecha, L., 1997. Tillage effects on water runoff and soil erosion after sod. J. Soil Water Conserv. 53, 59–63.

Mathcad, 2000. MathSoft, Inc., 101 Main Street, Cambridge, MA, USA.

McGarry, D., Bridge, B., Radford, B., 2000. Contrasting soil physical properties after zero and traditional tillage of an alluvial soil in the semi-arid subtropics. Soil Tillage Res. 53, 105–115.

Melesse, T., Rockstrom, J., Savenije, H.H.G., Hoogmoed, W.B., Dawit, A., 2008. Determinants of tillage frequency among smallholder farmers in two semi-arid areas in Ethiopia. Phys. Chem. Earth 33, 183–191.

Mikha, M., Rice, C., 2004. Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. Soil Sci. Am. J. 68, 809–816.

Moeyersons, J., Nyssen, J., Poesen, J., Deckers, S., Mitiku, H., 2006. On the origin of rock fragment mulches on Vertisols: a case study from the Ethiopian highlands. Geomorphology 76, 411–429.

Moreno, F., Pelegrin, F., Ferdinandez, J., Murillo, J., 1997. Soil physical properties, water depletion and crop development under traditional and conservation tillage in Southern Spain. Soil Tillage Res. 41, 25–42.

MU-IUC, 2007. Digital database of climatologically and stream flow data of Geba catchment. VLIR (Belgium)-Mekelle University (Ethiopia). Institutional University Cooperation Program, Mekelle and Leuven.

Mulugeta, L., Karltun, E., Olsson, M., 2005. Assessing soil chemical and physical property responses to deforestation and subsequent cultivation in smallholders farming system in Ethiopia. Agric. Ecosys. Environ. 105, 373–386.

NEDECO, 1997. Tekeze river basin integrated development master plan. A report by The Netherlands Engineering Consultants and Ministry of Water Resources (Ethiopia). Addis Ababa, Ethiopia.

Nyssen, J., Poesen, J., Mitiku, H., Moeyersons, J., Deckers, S., 2000. Tillage erosion on slopes with soil conservation structures in the Ethiopian highlands. Soil Tillage Res. 57, 115–127.

Nyssen, J., Govaerts, B., Mintesinot, B., Mitiku, H., Sayre, K., Tigist, O., Fisseha, M., Mekonnen, G., Solomon, G., Tewodros, G., Fekadu, G., Nurhussen, T., Wubetu, B., Poesen, J., Raes, D., Verplancke, H., Deckers, J., 2006. Conservation agriculture: a further step in sustainable agricultural intensification in the Northern Ethiopian highlands. In: De Dapper, M., De Lame, D. (Eds.), Proceedings of the International Conference ''Africa's Great Rift: Diversity and Unity''. Royal Academy for Overseas Sciences, Royal Museum for Central Africa, Brussels, 29–30 September 2005, pp. 169–183.

Nyssen, J., Naudts, J., De Geyndt, K., Mitiku Haile, Poesen, J., Moeyersons, J., Deckers, J., 2008. Soils and land use in the Tigray Highlands (Northern Ethiopia). Land Degrad. Dev. 19, 257–274.

Nyssen, J., Poesen, J., Mitiku Haile, Moeyersons, J., Deckers, J., Hurni, H., 2009. Effects of land use and land cover on sheet and rill erosion rates in the Tigray Highlands, Ethiopia. Zeitschrift für Geomorphologie 53 (2), 171–197.

Oorts, K., Bossuyt, H., Labreuche, J., Merckx, R., Nicolardot, B., 2007. Carbon and nitrogen stocks in relation to organic matter fractions, aggregation and pore size distribution in no-tillage and conventional tillage in northern France. Eur. J. Soil Sci. 58, 248–259.

Reynolds, W.D., Drury, C.F., Yang, X.M., Fox, C.A., Tan, C.S., Zhang, T.Q., 2007. Land management effects on the near-surface physical quality of a clay loam soil. Soil Tillage Res. 96, 316–330.

Rezene, F., Zerihun, T., 2001. Weed Research in Tef. In: Hailu, T., Getachew, B., Mark, S. (Eds.), Narrowing the Rift: Tef Research and Development. Proceedings of the International Workshop on tef Genetics and Improvement, DebreZeit, Ethiopia, 16–19 October 2000, pp. 201–213.

Rockström, J., Kaumbutho, P., Mwalley, J., Nzabi, A.W., Temesgen, M., Mawenya, L., Barron, J., Mutua, J., Damgaard-Larsen, S., 2009. Conservation farming strategy in East and Southern Africa: yields and rainwater productivity from on-farm action research. Soil Tillage Res. 103, 23–32.

SAS, 2002. JMP Software Version 5. SAS Institute Inc., Cary, NC, USA.

Sasakawa Global SG-2000/Ethiopia, 2004. Proceedings of the Workshop on Conservation Tillage. Melkassa Agricultural Research Center, East Shewa, Ethiopia.

Seyfu, K., 1997. Tef. *Eragrostis tef* (Zucc.) Trotter. Promoting the conservation and use of underutilized and neglected crops. 12. Institute of Plant Genetics and Crop Plant Research, Gatersleben/International Plant Genetic Resources Institute, Rome, Italy.

Smith, J.L., Elliott, L.F., 1990. Tillage and residue management effects on soil organic matter dynamics in semiarid regions. In: Singh, R.P., Parr, J.F., Stewart, B.A. (Eds.), Dryland Agriculture—Strategies for Sustainability. Springer, New York, pp. 68–88.

Solomon, G., Mouazen, A., Van Brussel, H., Ramon, H., Nyssen, J., Verplancke, H., Mintesinot, B., Deckers, J., De Baerdemaeker, J., 2006. Animal drawn tillage, the Ethiopian ard plough, *maresha*: a review. Soil Tillage Res. 89, 129–143.

Taddesse, E., 1969. Tef (*Eragrostis tef*): The cultivation usage and some of the unknown disease and insect pests. Part I. Debrezeit Agricultural Experiment station Bulletin No. 60. Haileselassie I University, College of Agriculture, Dire Dawa, Ethiopia.

Tariq, A., Durnford, S., 1993. Soil volumetric shrinkage measurements: a simple method. Soil Sci. 155, 325–330.

USDA, 1999. Soil Taxonomy, A Basic System of soil Classification for Making and Interpreting Soil Surveys, 2nd ed., Agriculture Handbook Number 436. U.S. Department of Agriculture, Natural Resources Conservation Service, 870 pp.

Van Genuchten, M., 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Am. J. 44, 892–898.

Van Genuchten, M., Simunek, J., Leij, F., Segna, M., 1991. Code for Quantifying the Hydraulic Functions of Unsaturated Soils. US Salinity Laboratory USDA, ARS, Riverside, USA.

Walkley, A., Black, C.A., 1934. Estimation of organic carbon by chromic acid titration method. Soil Sci. 37, 29–38.

Whalen, J., Quancai, H., Aiguo, L., 2004. Compost application increase water stable aggregates in conventional and no tillage systems. Soil Sci. Am. J. 67, 1842–1847.

Wolde, M., Veldkamp, E., Mitiku, H., Nyssen, J., Muys, B., Kindeya, G., 2007. Effectiveness of exclosures to restore degraded soils as a result of overgrazing in Tigray, Ethiopia. J. Arid Environ. 69, 270–284.

WRB, 1998. World Reference Base for Soil Resources: World Soil Resources Reports. International Society of Soil Science, Food and Agriculture Organization of the United Nations, Rome.

Zhang, G.S., Chan, K.Y., Oates, A., Heenan, D.P., Huang, G.B., 2007. Relationship between soil structure and runoff/soil loss after 24 years of conservation tillage. Soil Tillage Res. 92, 122–128.